Assessing Snowmelt Runoff: a Comprehensive Review of Snowmelt Runoff Model

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***Abstract*— The purpose of this review study is to assess how well the WinSRM (Snowmelt Runoff Model) simulates runoff from melting, which is important for hydrological forecasting and water resource management. By thoroughly examining the current literature and case studies, we evaluate the advantages, disadvantages, and suitability of WinSRM for a range of environmental circumstances. We draw attention to the model's ability to accurately represent important hydrological processes, including runoff production, infiltration, and snowmelt and accumulation. In addition, we go over the lessons learned from case studies carried out in different areas, which help to clarify the model's dependability and its consequences for water resource management plans. All things considered, this study offers scholars, professionals, and decision-makers engaged in hydrological modeling and management insightful information.**

Keywords—Snowmelt Runoff Model, WinSRM, Hydrological Modeling, Snowmelt Runoff, Snow Cover

I. INTRODUCTION

Understanding hydrological processes, especially in areas where snowmelt has a major impact on the water cycle, depends heavily on snowmelt runoff models [1]. For many uses, such as flood forecasting, water resource management, and research on the effects of climate change, accurate evaluation of snowmelt runoff models is crucial [1]. We examine one such model, WinSRM [5], in-depth in this thorough analysis to shed light on its effectiveness and suitability. Among the numerous snowmelt runoff models available, WinSRM has emerged as a prominent tool for simulating snowmelt runoff processes. WinSRM employs a comprehensive approach that integrates meteorological data, snowpack physics, and hydrological principles to predict runoff dynamics. Its versatility and user-friendly interface have made it a preferred choice for researchers and practitioners alike [1, 12].

The objective of this study is to present a thorough evaluation of WinSRM's effectiveness by examining case studies carried out in diverse hydrological environments. Through a critical assessment of WinSRM's advantages and disadvantages, we want to provide insightful information on how well-suited it is for use in various geographic and climate contexts. Furthermore, to illustrate WinSRM's relative benefits and drawbacks, we compare it with other snowmelt runoff models currently in use.

II. SNOWMELT RUNOFF MODEL (WINSRM)

In mountain basins where snowmelt plays a significant role in runoff, the Snowmelt-Runoff Model (WinSRM) is intended to model and forecast daily streamflow. The basin or zonal snow cover extent from remote sensing is needed to feed the straightforward degree-day Snowmelt Runoff Model (SRM) [21]. Martinec was the one who created SRM (1975). The SRM's runoff calculations seem to be quite simple to understand.

SRM can be used for the following purposes:

(1) Daily flow simulation during a snowmelt season, a year, or a series of years [1].
(2) Seasonal and short-term runoff projections [5].
(3) The possible impact of climate change on the seasonal snow cover and runoff was assessed using SRM [3].

A. *Temperature Index Approach:*

Conceptual Index Approach [1, 5, 11] is another name for the Temperature Index Approach. The snowpack energy exchange is approximated using air temperature. Empirical models predicated on the idea that the mean daily air temperature and the rate of snowmelt have a linear connection as fewer input parameters were needed [13, 21].

The temperature index approach for snowmelt runoff modeling involves several key formulas and calculations such as Degree Day [6, 17] calculation, Snowmelt rate, and Snowmelt Runoff Estimation [1, 19].

B. *Energy Balance Approach:*

The Energy balance approach [20] employed by the Snowmelt Runoff Model (WinSRM) integrates various factors influencing snowmelt runoff, ensuring comprehensive analysis. It considers incoming solar radiation, energy exchanges at the snow surface, and heat transfer within the snowpack [16]. By accounting for these elements, WinSRM accurately simulates snowmelt processes, crucial for water resource management and flood forecasting. This approach calculates snow accumulation and ablation, incorporating meteorological data to predict runoff dynamics [9, 18]. Through its holistic assessment of energy fluxes, WinSRM enhances understanding of snowmelt-driven hydrological systems, aiding decision-making in water management and environmental planning [20].

C. *WinSRM Model Structure:*

The water produced from snowmelt and rainfall is computed, superimposed on the calculated recession flow, and transformed into daily discharge from the basin according to Equation [21]:

$$\mathrm{Q_{n+1}} = [\mathrm{C_{sn}a_n(T_n + \Delta T_n)S_n + C_{Rn}P_n}]\frac{\mathrm{A.10{,}000}}{86{,}400}(1 - \mathrm{k_{n+1}}) + \mathrm{Q_n k_{n+1}}$$

Q = average daily discharge [m3s-1]

C =runoff coefficient expressing the losses as a ratio (runoff/precipitation), with C_S referring to snowmelt and C_R to rain

a = degree-day factor [cm oC-1d-1] indicating the snowmelt depth resulting from 1 degree-day

T = number of degree-days [oC d]

ΔT = the adjustment by temperature lapse rate

S = ratio of the snow-covered area to the total area

P = precipitation contributing to runoff [cm]

A = area of the basin or zone [km2]

k = recession coefficient indicating the decline of discharge in a period without snowmelt or rainfall: $\mathrm{k} = \frac{\mathrm{Q_{n+1}}}{\mathrm{Q_n}}$ (m, m + 1 are the sequence of days during a true recession flow period)

n = sequence of days during the discharge computation period

T, S, and P are variables to be measured or determined each day, C_S & C_R, lapse rate to determine ΔT, T_{CRIT}, k, and the lag time are parameters that are characteristic for a given basin or, more generally, for a given climate.

D. *WinSRM Input Data & Parameters:*

Basin Characteristics	***Variables***	***Parameters***
Elevation Zonal Area (sq. km) Hypsometric Zonal Mean Elevation (m)	Precipitation (cm) Temperature (^{O}C) Fractional Snow Cover	Runoff Coefficient (Rainfall & Snow) Degree Day Factor Temperature Lapse Rate (^{o}C) Critical Temperature (^{o}C) Time Lag (hr) Rainfall Contributing Area X Recession Coefficient Y Recession Coefficient

E. *Snowmelt Runoff Model Applications:*

WinSRM has a wide range of Applications in the field of Snow Hydrology. Some of them are:

a. Snowmelt Runoff
b. Flood Forecasting
c. Climate Change Impact
d. Hydropower Generation
e. Ecosystem Management
f. Water Resources Planning and Management
g. Adverse Effects of Snow Basins

F. *Accuracy of WinSRM Model:*

The Snowmelt Runoff Model uses the coefficient of determination (R^2) and Deviation of runoff volumes (D_v) to assess the accuracy of the model [21, 18]:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(Q_i - Q_i')^2}{\sum_{i=1}^{n}(Q_i - \bar{Q})^2} \qquad D_v(\%) = \frac{V_R - V_R'}{V_R} \times 100$$

III. Case Studies – Snowmelt Runoff Model (WinSRM)

Snowmelt RunoffModel (SRM) is used to calculate the snowmelt contribution to the Beas River's overall streamflow up to the Pandoh dam. The snow cover in the research region has been calculated and the area is split into seven elevation classes. The amount of the basin that is covered in snow ranges from 10% to 80%. The Coefficient of Determination (R^2), Nash-Sutcliffe Efficiency (NSE), and Volume Difference (D_V) were used to assess the model's efficiency. R^2, NSE, and D_V ranged from 0.79 to 0.87, 0.72 to 0.79, -0.025% to 7.2%, and 0.72, 0.67, -4.65%, respectively, over the calibration and validation periods. The study's main conclusions indicate that the summer and monsoon seasons produce the majority of streamflow, with snowmelt contributing to ranges from 10-45% [1].

A simple degree-day model (SRM) was used to simulate snowmelt runoff in the Himalayan region's Lidder River basin to assess the hydrological effects of climate change. Volume difference (Dv) and coefficient of determination (R2) indicate that the SRM model worked well during calibration and validation. Between 2009 and 2014, the Dv values were 11.7%, −10.1%, −11.8%, 1.96%, and 8.6 correspondingly, while the corresponding R2 values were 0.96%, 0.95%, 0.90%, and 0.94. The results of the simulations demonstrated that the predicted snowmelt runoff closely resembles the observed values. Three distinct climate change scenarios were used to evaluate the simulated results: (a) increased precipitation by 20%; (b) increased temperature by 2°C; and (c) a 20% rise in snow cover (d) increased runoff by 53 % (e) estimated a 37% rise in discharge (f) increased by 67 % [2].

Forecasting the flow mainly due to snowmelt in the mountains of Eastern Turkey is important for the effective management of water resources in the headwaters of the Euphrates River with large reservoirs. Snow Covered Area (SCA) monitoring and snowmelt modeling form the backbone of the forecast study, as runoff controlled by snowmelt accounts for approximately 2/3 of the annual runoff in spring and early summer. The two main motives for the study are; First, an evaluation of SCA prediction methods using Moderate Resolution Imaging Spectroradiometer (MODIS) data and a snow particle curve (SDC) derivative for each altitudinal zone. Second, predict upcoming daily flows using derived SDCs and numerical weather forecast (NWP) data adapted for the region. The Upper Euphrates watershed (10,275 km2) is selected as a pilot and MODIS snow cover products are analyzed daily for snowmelt time. Four different methods are proposed and evaluated to predict SDCs; simple average, temperature-based, stochastic modeling, and probability calculus. The SDC was run from 2006 to 2010, with four years of data used to derive the method equations and one year to test their capability. The second part of the study predicts emissions for 1 day using the Snowmelt Runoff model using NWP data. The model examines the effects of 4,444 predicted SDCs using different methods. Applications of the model show promising results in predicting both SCA and runoff, with overall model efficiencies above 0.60 and 0.85 [3].

From 2000 to 2006, the Upper Indus Basin along the Astore River in northern Pakistan was subjected to the snowmelt runoff model (SRM). A digital elevation model (DEM) region is created using data from the Shuttle Radar Topographic Mission (SRTM). The SRM receives input from a variety of sources, including temperature, precipitation, runoff coefficients, critical temperature, critical temperature lag rate, degree-day coefficient, regression coefficient, and runoff coefficients. Snow cover data, however, is a direct and crucial input for SRM. The SCA is estimated using satellite data from the Moderate Resolution Imaging Spectroradiometer (MODIS). To map snow cover and differentiate snow from other terrain characteristics, one can utilize the normalized Differential Snow Index (NDSI) technique. The quality of SRM is assessed using the volume difference (DV) and the Nash-Sutcliffe coefficient of determination (R2). The current study's findings indicate that, for the study years (2000-2006), the average volume difference (DV) is 1Ô18% and the average R2 is 0Ð87. The estimated and measured runoff had a 0.95 correlation coefficient. The study's findings also demonstrate that the snowmelt season is a good time to obtain high accuracy levels. The simulation findings validate the great use of the SRM with MODIS snow cover product for managing the water resources of the Astore River and for projecting runoff in the northern Pakistani Indus River basin [4].

Glacier Lake Outburst means a sudden and rapid release of water from a glacial lake. In June, there was a big flood in Kedarnath. In 2013, information was collected from different sources to create a model. Field and Remote Sensing (RS) are used to study the Earth's surface from a distance. The dam was broken and the water from the lake flowed out. Measurements like size, depth, break, and tallness. Field observations have been used to make an estimate. Remote sensing data. Several models' Different methods, like the Snow Melt Runoff Model, are used to study this. (SRM) and Modified Single Flow model (MSF) are two different models. Watershed Management System (WMS) made easier Dam Breach Model (SMPDBK) and BREACH was SMPDBK and BREACH were model for studying dam breaches. Used to create a model of the GLOF. SRM's guesses made 22. 7 cubic meters of runoff in 2016-2017. In June 2013, at Chorabari Lake. Bathymetry information about the depths of the ocean floor. The report said that the lake was full. The container can hold 3822. 7 cubic meters of liquid because there is too much pouring out. Hydrograph received from the BREACH model. A high flow of about 1699 cubic meters per second was found during. a strong stream of water that lasted for 10 to 15 minutes on June 17th, 2013, the meeting lasted for 45 minutes. Too much leaking from the lake got bigger because there was lots of rain and the snow melted [5].

The Himalayan area is seeing a significant increase in temperature, which might have a significant impact on the Indus River's future flows. Thus, for the Upper Indus Basin's (UIB) future water resource management, snow, and glacier melt flow prediction is essential. To predict the Gilgit River's daily streamflow in the Karakoram area, a snowmelt runoff model (SRM) was employed in conjunction with MODIS remote sensing data. Using model efficiencies of 0.96, 0.86, 0.9, and 0.94, simulations were run over four years, from 2007 to 2010, once the SRM had been correctly calibrated. To predict future Gilgit River flows, the SRM model employed precipitation and mean temperature scenarios created by the regional climate model PRECIS. Gilgit river flows might rise by 35–40% if the mean annual temperature increases by 3 C by the end of the twenty-first century. Future irrigation and hydropower generation in the Indus basin will require improved water storage and management due to the anticipated rise in surface water runoff brought on by snow and glacier melting [6].

A significant portion of 4,444 mountain basins' water supply comes from runoff from snowmelt. In the Taleghan Basin of Iran, this study employed a snowmelt model (SRM) to estimate snowmelt runoff. In mountain watersheds, daily streamflow has been estimated using the SRM hydrologic model. Using meteorological, hydrologic, and physical properties of the basin as inputs, this model computes snowmelt runoff and presents the findings both numerically and visually, accompanied by the observed runoff. The major outputs of SRM are temperatures, hence the goal of this work is to assess the degree and radiation of SRM and to offer a suitable approach for interpolating temperatures. After determining the values of these input parameters, the model simulation was run. Hydrographs that were computed and observed were plotted. The hydrographs were compared using the percent difference in volume (Dv), the Nash-Sutcliffe coefficient of efficiency (NSE), and ocular examination. In the validation period, the estimated values of NSE for radiation models and degree-day models were 0.80 to 0.88 and 0.65 to 0.86, respectively. According to estimates, Dv during the validation period ranged from 1.85 to 18.36-degree days in the radiation model and -0.65 to -4.54 in the temperature model. Using the SRM degree-day and radiation models, seven distinct temperature interpolation techniques were used throughout the Taleghan Basin. The findings demonstrated that discrepancies between estimated and actual runoff might originate from temperature estimating techniques. Additionally, the temperature interpolation approach and the addition of the radiation coefficient to the model will considerably improve the simulation's accuracy and describe the hydrological behavior of snow, therefore eliminating the shortage of measurement data in snowmelt flow modeling. a body of water inside the cities [7].

The flow of snowmelt in the dao-Songhua Basin in the upper Songhuajiang Basin is simulated from March to August 2010 using a snowmelt runoff model (SRM). DEM information. The daily Terra/Aqua products are used to construct the MODIS flexible snow cover products (MODISMC), which are utilized as the snow cover area input for the SRM model. To get the daily mean temperature and precipitation for each zone, Kriging techniques are used to interpolate temperature and precipitation data from climate stations. With three variables and eight parameters, the SRM model is obliged to take into consideration the hydrological and physical aspects of the research region. Snowmelt peaks between mid-April and late May, according to the results. There is a difference of 25.59% and 0.57 between the runoff amount (Dv) and the Nash-Sutcliffe coefficient of determination (R2). The snowmelt process was neglected, and there were insufficient in situ materials, which is the primary cause of the model inaccuracies [8].

A modified version of the improved temperature index snowmelt flow model (SRM), in which the degree-day factor (DDF) is affected by shortwave solar radiation and snow albedo, was used to evaluate the feasibility of simulating daily snowmelt flow in a dry alpine location with limited hydrometeorological observations. Model efficiencies of 0-64 in the calibration year and 0-78 and 0-51 in the two validation years showed that the model adequately represented snowmelt runoff. According to the research, the model is dependent on the characteristics related to snow albedo and fragmentation. What made the simulation effective was the obvious seasonal change in the failure rate. More validation is required, however, for the watershed, a snow albedo parameterization that scaled snow cover by % directly to snow albedo worked rather well. The model was fed with snow cover data collected over eight days using the Moderate Resolution Imaging Spectroradiometer (MODIS). The frequency filter enhanced the model's performance by eliminating clouds and significant fluctuations in snow cover from the MODIS snow cover data [9].

In the eastern Himalayan area, in particular, a significant obstacle to estimating snowmelt flows is a lack of data. With a huge database in Arunachal Pradesh, a small representative seasonally snow-covered eastern Himalayan watershed has been used as the source of snowmelt flow estimates in this work using a Windows-based snowmelt model (WinSRM). With a height differential of almost 1800 meters between the lowest and highest points, the 52 km2 catchment area is split into three altitude zones due to its extremely steep middle slope. From the Indian Remote Sensing Satellite IRS-P6 (LISS-III/AWiFS), satellite photos of the town were provided. The Normalized Snow Index (NDSI) approach is utilized for mapping snow cover. The daily snow-covered area (SCA%), which is also uncommon during snow loss in that location, is generated by interpolating the periodic SCA% found from cloud photos to create snow decrease curves for each zone. Since a cloud-free IRS-P6 satellite picture was not available for the 2004 validation period, a logarithmic connection is constructed between the percent SCA and mean air temperature (AMAT) to estimate the percent SCA for that time. The WinSRM model is verified for the 2004 depletion period and calibrated using three years of data from the 2006, 2007, and 2009 depletion periods. It has been demonstrated that in such scarce watersheds in the Eastern Himalayas, the SRM model may be applied successfully [10].

Comparison with other Models:

Physical Basis:
WinSRM employs a degree-day method, which calculates snowmelt based on the degree-days [19] above a specified threshold temperature. Other snow models like SNOW-17 and SNTHERM typically use energy balance principles, considering factors such as solar radiation, air temperature, wind speed, and humidity to simulate snowpack evolution [13, 14].

Spatial and Temporal Resolution:
WinSRM generally, operates at a daily time step and can be applied at various spatial scales, from small catchments to larger river basins. Other models may offer higher temporal and spatial resolutions [20], allowing for more detailed simulations but requiring more computational resources.

Input Requirements:
WinSRM requires inputs such as precipitation, temperature, and possibly snow-water equivalent (SWE) observations. Other models may require additional inputs such as wind speed, humidity, solar radiation, and topographic information [14].

Model Complexity:
WinSRM [17] is relatively simple compared to some other models, making it easier to set up and run. More advanced models may incorporate complex algorithms to represent processes such as snow redistribution by wind, snow compaction, and the effects of vegetation on snow accumulation and melt.

Calibration and Validation:
WinSRM Calibration involves adjusting parameters such as the degree-day factor [19] to match observed streamflow or SWE data. Other models may have more parameters to calibrate and validate, and their performance can vary depending on the region and specific conditions.

Applicability:
WinSRM [17] is widely used in various regions for water resources management, flood forecasting, and climate change impact assessments. Other models may be preferred in certain situations, such as when detailed physical processes need to be represented or when higher-resolution simulations are required.

Availability and Support:
WinSRM was developed by the USDA Agricultural Research Service and is available for download and use by the public. Other models may have different levels of availability, documentation, and user support.

IV. CHALLENGES AND FUTURE DIRECTIONS

Challenges in the Snowmelt Runoff Model:
Simplified Representation: WinSRM simplifies the complex processes of snowmelt and runoff into mathematical models, which may not fully capture all the intricacies of real-world conditions.

Input Data Requirements: The accuracy of WinSRM outputs depends heavily on the quality and resolution of input data, such as meteorological data, soil properties, and land use/land cover data. Inaccurate or insufficient input data can lead to unreliable results.

Assumptions and Parameterization: Like any model, WinSRM operates based on a set of assumptions and requires parameterization. These assumptions and parameters may not always perfectly represent the actual conditions of a watershed, leading to uncertainties in the model results.

Climate Change Impact: Climate change is likely to alter snowmelt patterns, affecting the accuracy of WinSRM's predictions of runoff timing and volume, and challenging water resource management [3, 15].

Limited Spatial and Temporal Resolution: WinSRM operates at a specific spatial and temporal resolution, which may not be fine enough to capture localized or short-duration events accurately. Higher resolution data may be required for more detailed analyses.

Validation and Calibration: Proper validation and calibration of the WinSRM model are essential for ensuring its reliability and accuracy. However, the availability of observed data for calibration may be limited, especially in remote or poorly monitored watersheds [2].

Complex Terrain and Heterogeneity: WinSRM may struggle to accurately simulate snowmelt and runoff processes in watersheds with complex terrain or heterogeneous land cover. These conditions can introduce additional challenges in parameterization and modeling.

Limited Process Representation: While WinSRM considers various processes such as snow accumulation, snowmelt, infiltration, and runoff generation, it may not include all relevant processes or interactions occurring within the watershed.

Future Directions in Snowmelt Runoff Model:

- The many contributions, such as base flow runoff, precipitation runoff, and glacier melt, that will be covered by hydrological modeling in the Basin in the future are not included in the Snowmelt Runoff Model (WinSRM).
- The results of current techniques have been used in the analysis of the rate of climate change as well as the creation of green energy.
- SRM did not simulate peak stream flows well which will be a current and future scope. The model needs to be incorporated with more physical processes.
- Adding radiation factors will be helpful in simulating stream flows under climate change scenarios.
- Incorporating more sophisticated remote sensing data such as LiDAR can be a prospect for the Snowmelt Runoff Model.

V. CONCLUSION

This review paper has provided a comprehensive analysis of the snowmelt runoff model, with a specific focus on WinSRM and its application through case studies. Through an in-depth examination of various aspects including model structure, parameterization, and accuracy of the model. we have highlighted the strengths and limitations of WinSRM in simulating snowmelt runoff processes.

Furthermore, insights gained from these case studies offer valuable guidance for improving model performance and enhancing its applicability in various water resource management scenarios. By addressing current limitations and leveraging emerging advancements in data assimilation, remote sensing, and modeling approaches, WinSRM and similar models hold great promise for improving our ability to predict and manage water resources in snow-influenced regions.

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